Low Emittance Muon Source for Muon $g-2$/EDM at J-PARC

Glen Marshall
TRIUMF
for the TRIUMF S1249 Collaboration
(KEK, RIKEN, and TRIUMF)
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Physics of Fundamental Symmetries and Interactions
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- Natural Sciences and Engineering Research Council, Canada
- TRIUMF, Canada's National Laboratory for Particle and Nuclear Physics

Outline

- An alternative method to measure muon anomalous magnetic moment $a_\mu = (g\!-\!2)/2$ and EDM

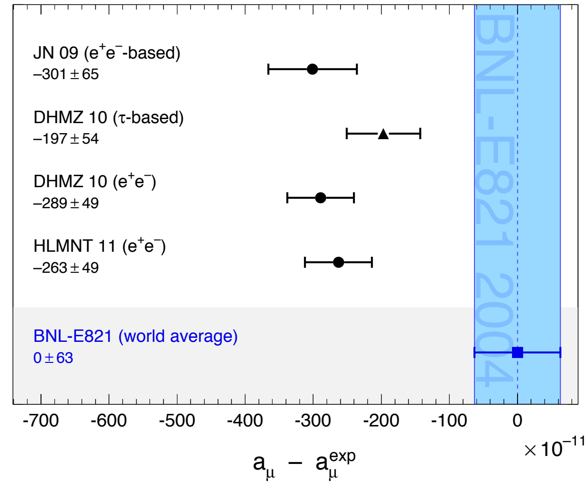
- Thermal muon beams: muonium (μ^+e^-) as an ion source

- Demonstration of muonium yields for the J-PARC muon $g\!-\!2$/EDM experiment

a_μ: Results of BNL E821

$$a_\mu^{\mathrm{E821}} = 116\ 592\ 091(54)(33) \times 10^{-11}$$
$$a_\mu^{\mathrm{SM}} = 116\ 591\ 803(1)(42)(26) \times 10^{-11}$$
$$\Delta a_\mu = a_\mu^{\mathrm{exp}} - a_\mu^{\mathrm{SM}} = 288(63)(49) \times 10^{-11}$$

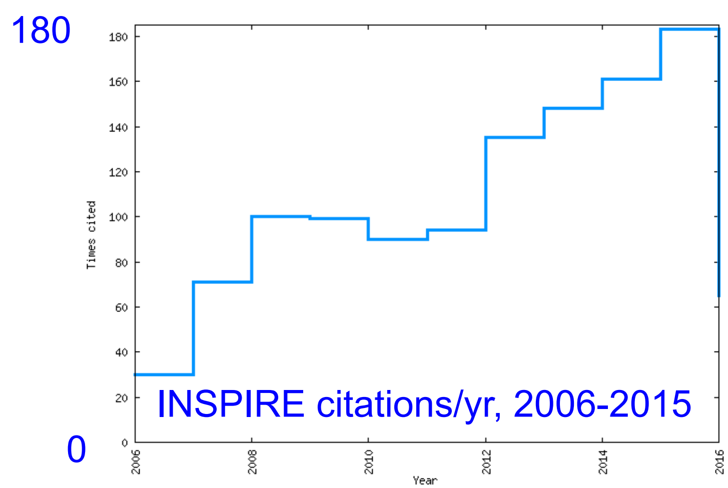
A. Hoecker and W.J. Marciano, PDG Review of Particle Properties (September 2014)



F. Jegerlehner and A. Nyffeler (JN), Phys. Reports 477, 1 (2009)
M. Davier et al. (DHMZ), Eur. Phys. J. C 71, 1515 (2011)
K. Hagiwara et al. (HLMNT), J. Phys. G 38, 085003 (2011)

- **anomalous moment a_μ differs from SM predictions by $\sim 3\sigma$**
- Motivates improvements in the SM prediction and experimental measurements
  - FNAL E989 (under construction)
  - *J-PARC E34 (proposed)*

G.W. Bennett and 75 others (E821), Phys. Rev. D 73, 072003 (2006)



J-PARC $g-2$/EDM *vs* FNAL989/BNL821

$$\vec{\omega}_a = \vec{\omega}_s - \vec{\omega}_c = -\frac{q}{m_\mu}\left[a_\mu \vec{B} - \left(a_\mu - \frac{1}{\gamma^2 - 1}\right)\frac{\vec{\beta}\times\vec{E}}{c}\right]$$

Fermilab (similar to BNL)

- eliminate effect of E-field via "magic" momentum:
  - $\gamma^2 = 1 + a^{-1}$
  - p_μ = 3.09 GeV/c required
- very uniform B
- electric quadrupole field focusing
- B = 1.45 T
- ρ = 7 m
- periodic calorimeters with some tracker modules

J-PARC

- eliminate effect of E-field via E = 0
- very uniform B in compact region
- weak B field focusing, no E focusing – must use low-emittance "cold" μ beam
  - polarization reduced to 50%
  - allows spin reversal
- choose p_μ = 0.3 GeV/c
- B = 3 T
- ρ = 0.33 m
- uniform tracker detection along stored orbit (EDM sensitivity)

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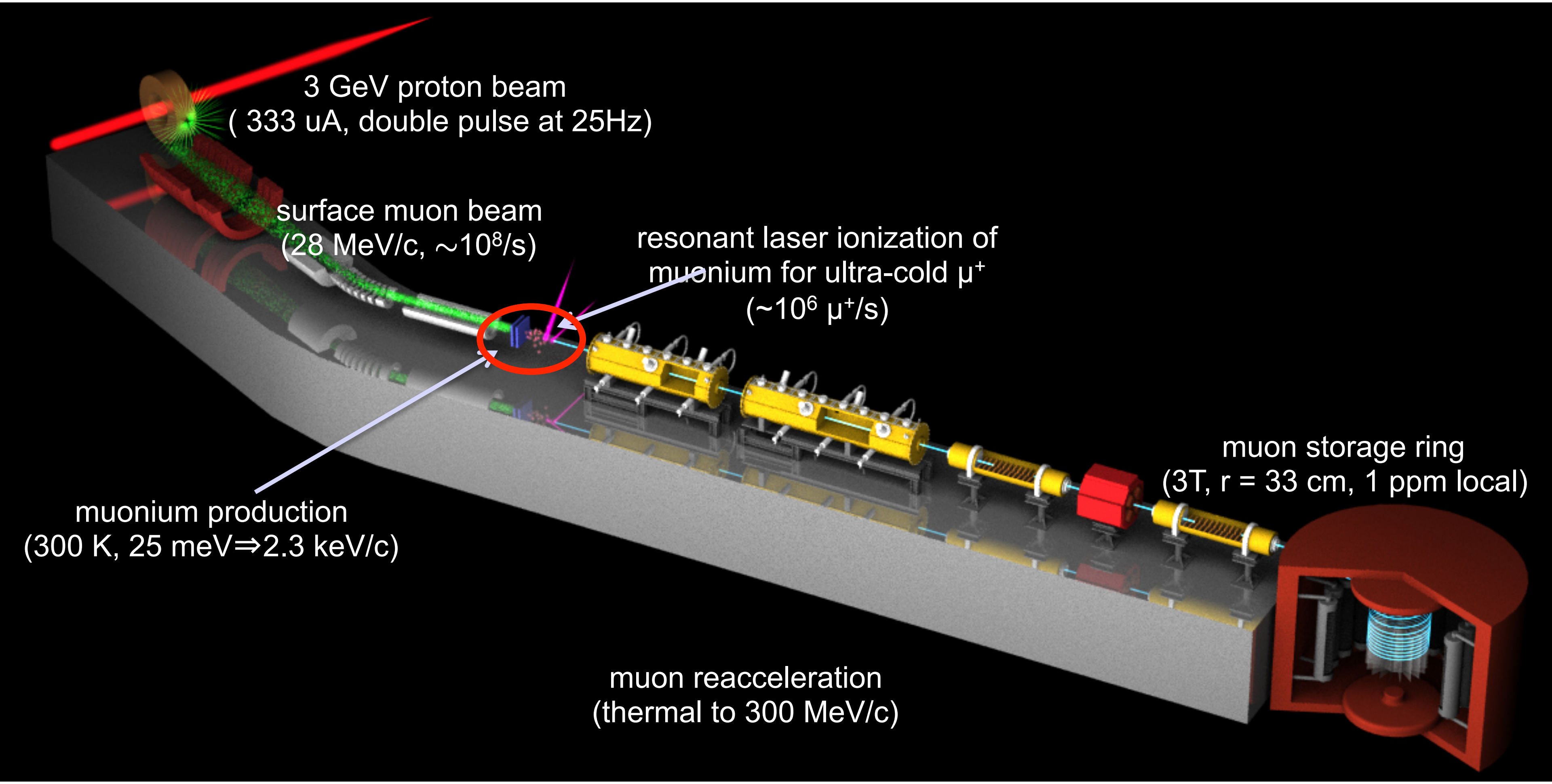
J-PARC g–2 schematic



J-PARC $g\!-\!2$ statistics goals (Stage 1)

Statistical uncertainties

- Goals
  - $\Delta\omega_a/\omega_a$ = 0.36 ppm (0.163/PN$^{1/2}$)
    - BNL E821 σ_{stat} = 0.46 ppm
  - $\Delta d_\mu = 1.3\times10^{-21}\ e\cdot\mathrm{cm}$
    - E821 $(-0.1\pm0.9)\times10^{-19}\ e\cdot$cm
    - $\Delta d_e < 1.05\times10^{-27}\ e\cdot$cm

Can we improve the conversion efficiency of the muon beam to ultra-slow muons?

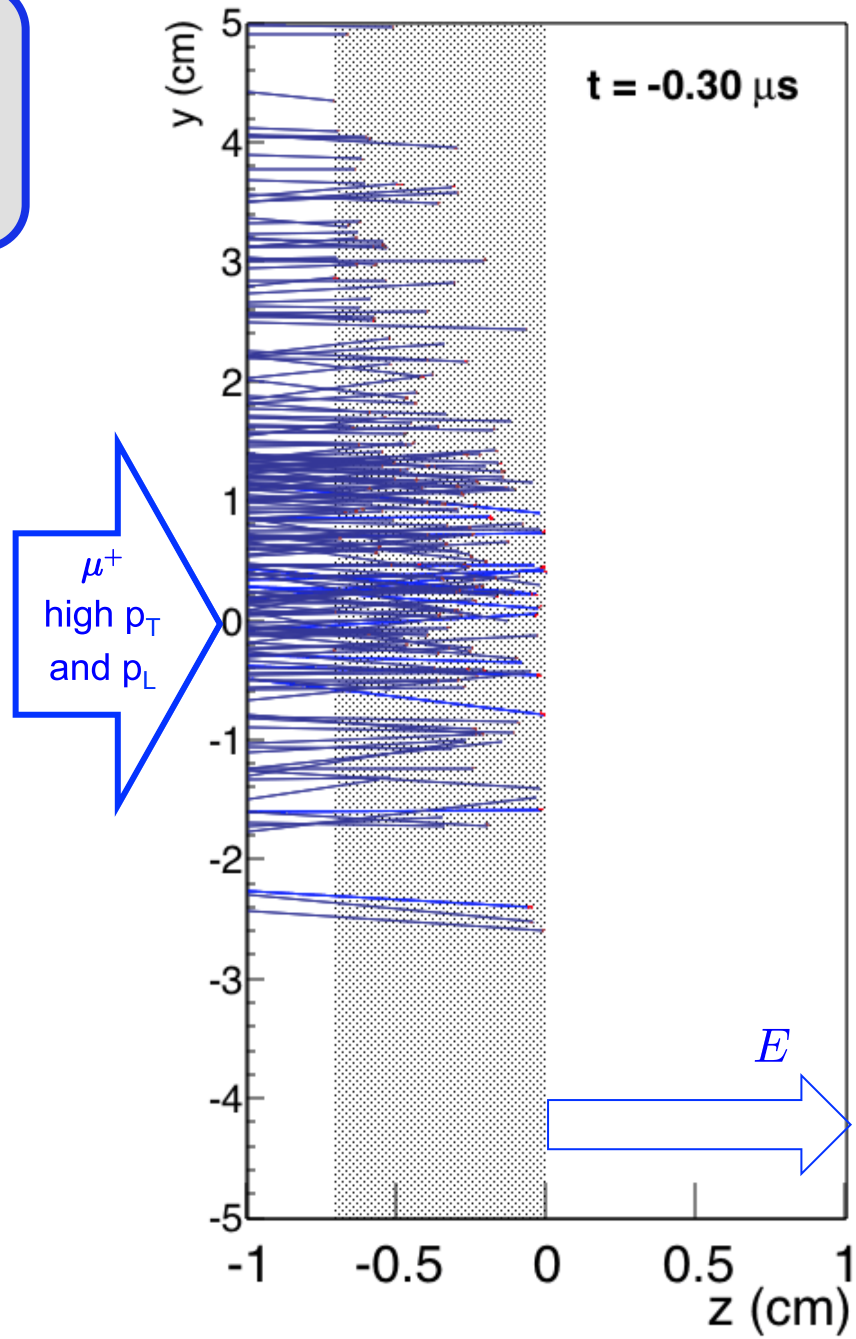
- Running time
  - measurement only: 2×10^7 s
- Muon rate from H-line
  - 1MW, SiC target: 3.2×10^8 s^{-1}
- Conversion efficiency to ultra-slow muons
  - Mu emission (S1249), laser ionization
  - lose polarization: 100% $\rightarrow$ 50%
  - 2.15×10^{-3} (*Stage 2 goal is 0.01*)
- Acceleration efficiency including decay
  - RFQ, IH, DAW, and high-β: 0.52
- Storage ring injection, decay, kick
  - 0.92
- Stored muons
  - 3.3×10^5 s^{-1}
- Detected positrons (ϵ = 0.12)
  - 4.0×10^4 s^{-1}

Surface muons to “cold” muons

- Thermalization of surface muons

	Surface beam	Thermal beam
E_k, MeV	3.4	0.03×10^{-6}
p, MeV/c	27	2.3×10^{-3}
$\Delta p/p$, rms	0.05	0.4
Δp, MeV/c	1.3	1×10^{-3}

- Thermal diffusion of Mu (μ^+e^-) into vacuum
  - decay length $\sim$14 mm



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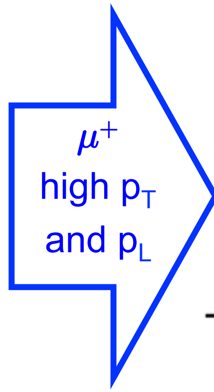

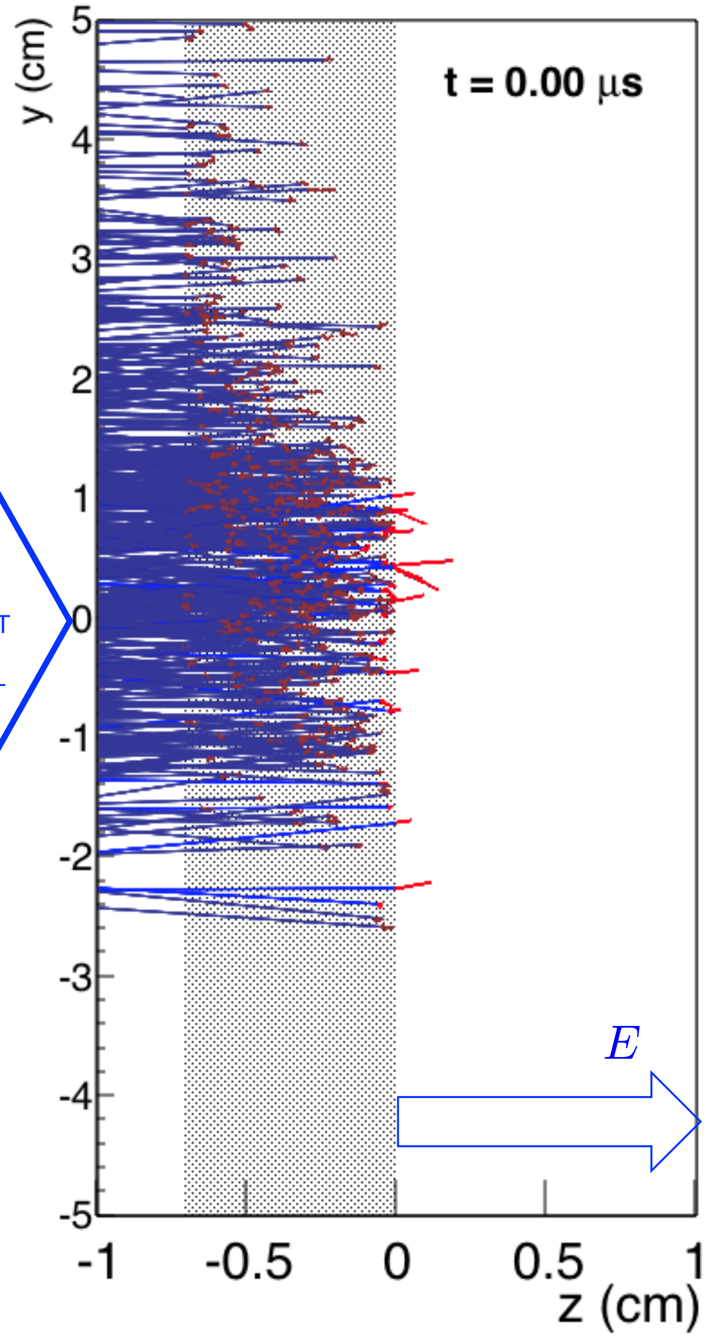

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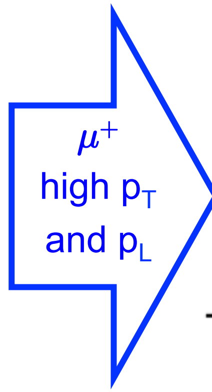

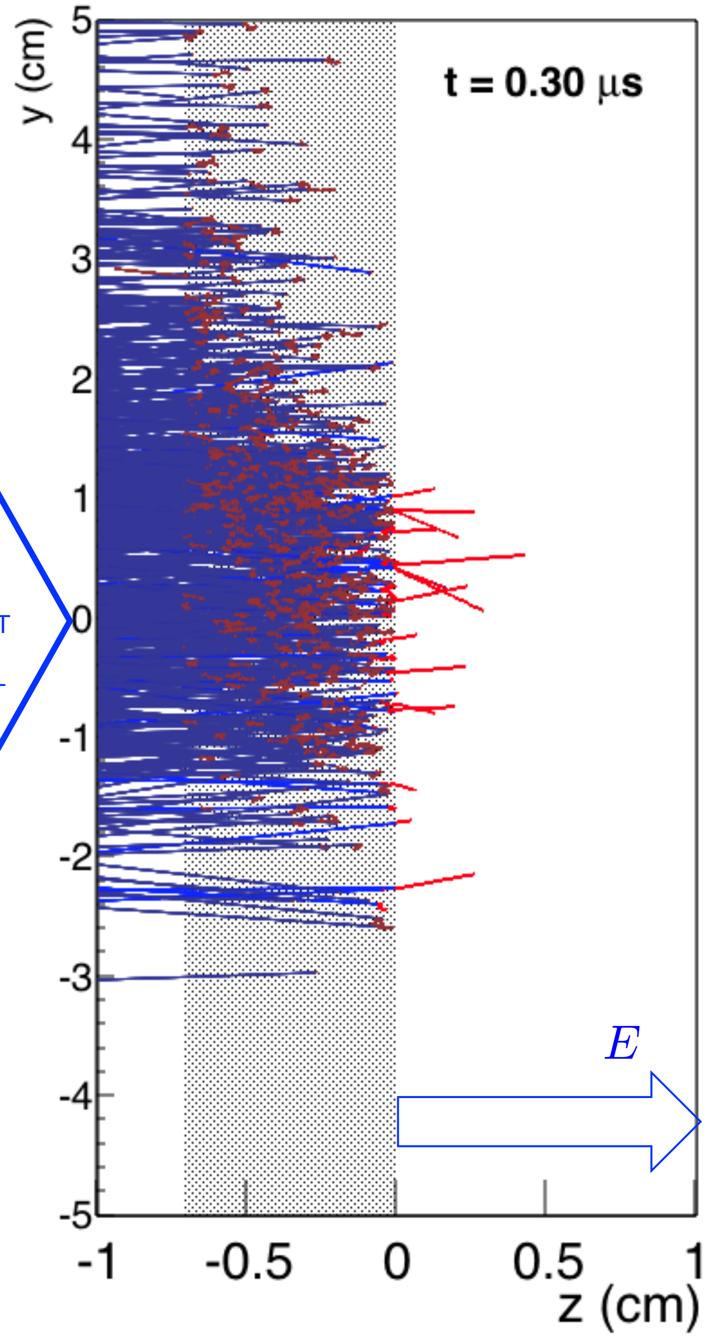

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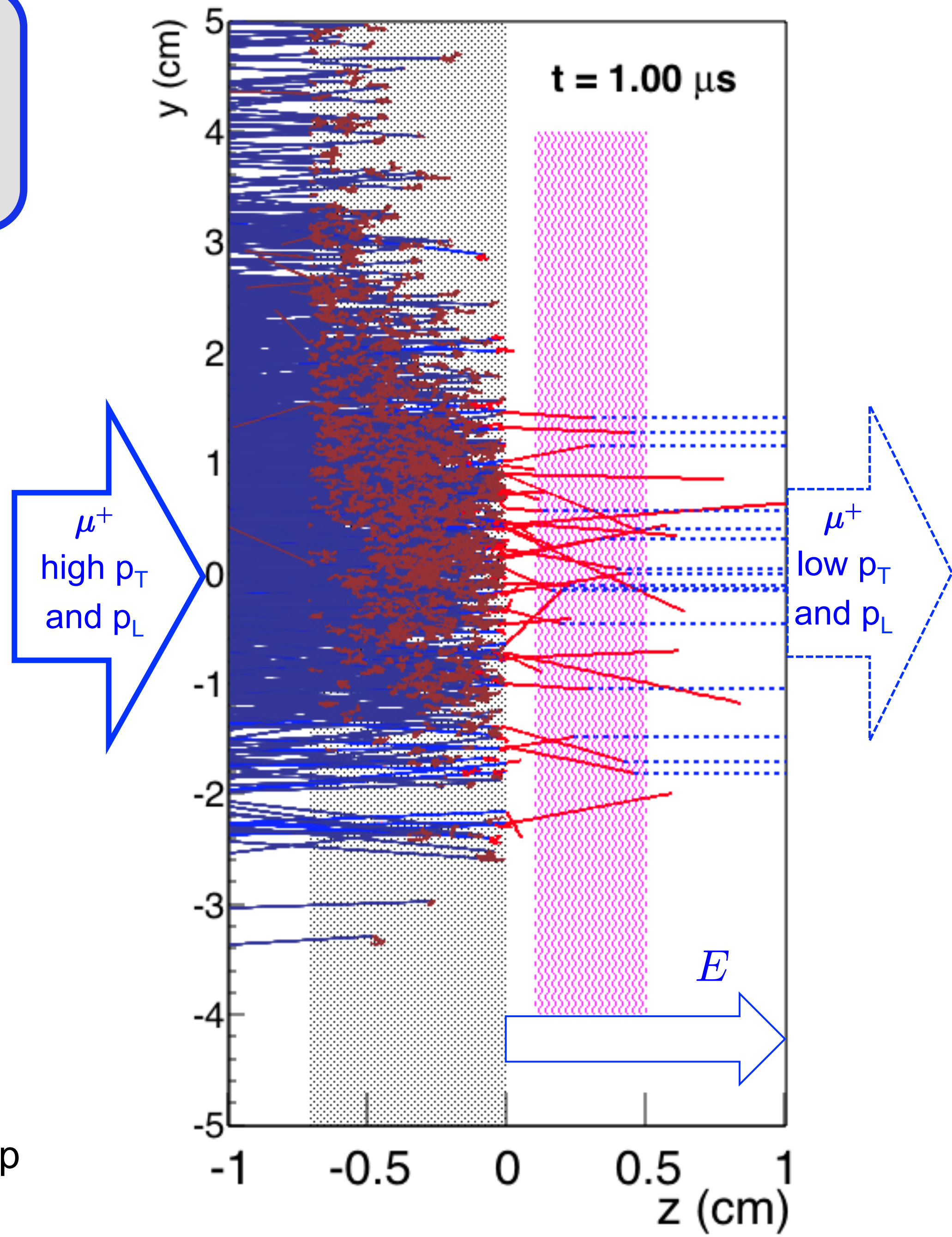
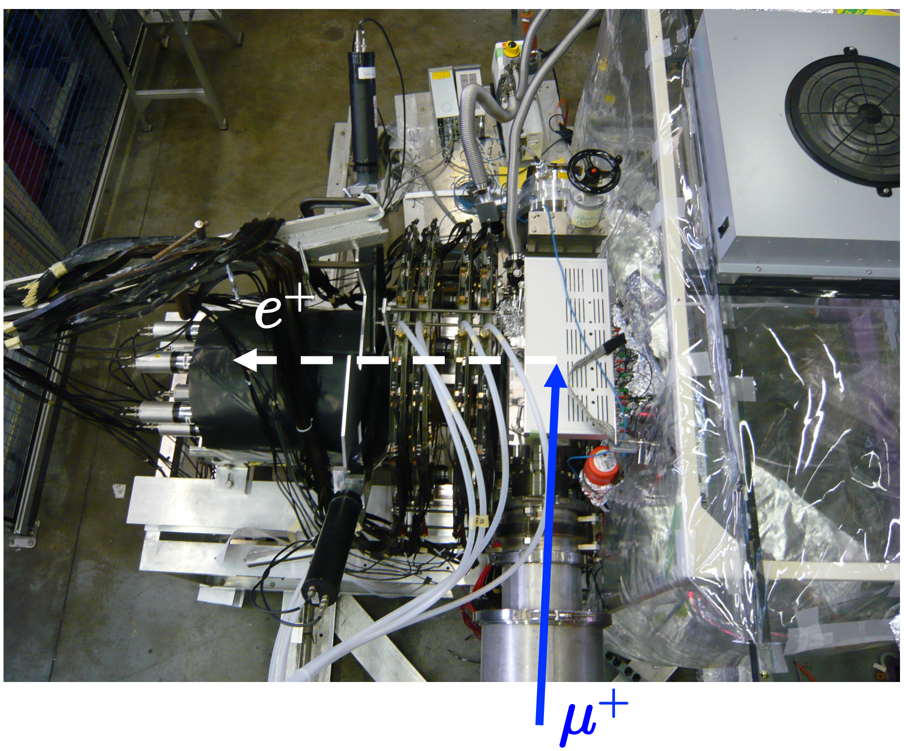
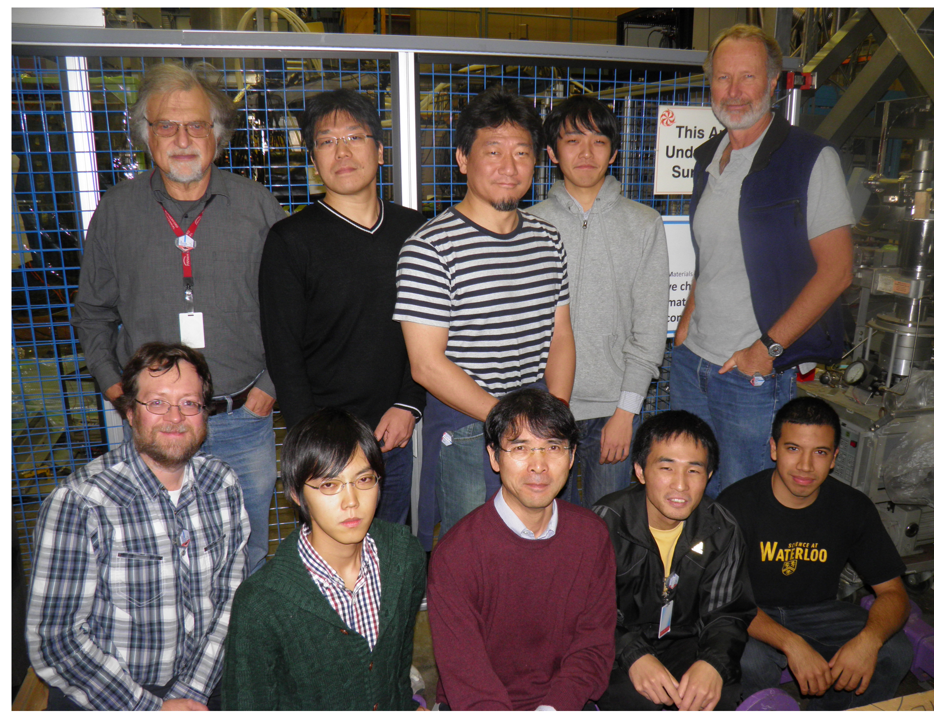
- Thermal diffusion of Mu (μ^+e^-) into vacuum
  - decay length $\sim$14 mm
- Ionization
  - 1S$\rightarrow$2P$\rightarrow$unbound (122 nm,355 nm)
- Acceleration
  - E field, RFQ, linear structures
  - adds to p_z but not significantly to Δp



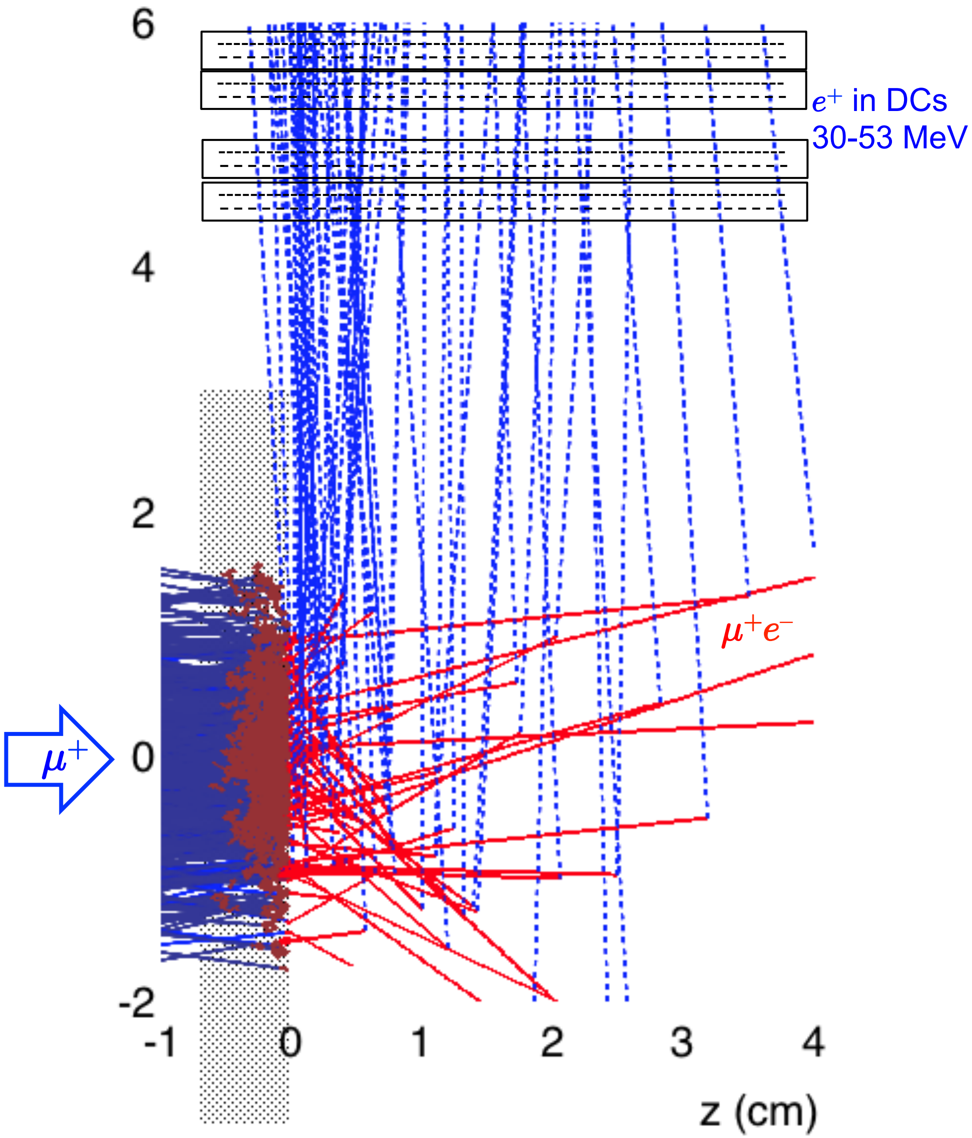
Muonium in vacuum – TRIUMF S1249

- Muonium (μ^+e^-, Mu) in vacuum was produced at TRIUMF many years ago for experiments to search for $\mu^+e^- \rightarrow \mu^-e^+$
- Other groups used similar methods at Los Alamos, PSI, RAL, and RIKEN, also for Mu spectroscopy
- A KEK/RIKEN/TRIUMF/UVic collaboration to develop Mu in vacuum for J-PARC g–2 began in 2009, using surface muons from TRIUMF





Identifying Mu in vacuum – TRIUMF S1249



- A multi-step process of:
  - μ^+ thermalization, μ^+e^- formation (52%, $\mathcal{P}_\mu$=50%).
  - μ^+e^- escapes into voids in evacuated silica *nanostructure* (~100%).
  - μ^+e^- migrates ("diffuses") to nearby material boundary (~ few %).
- Identify and characterize by:
  - time and position(y,z) correlations of muon decays from e^+ tracking (drift chambers).
- Muons decay in:
  - the target, as μ^+e^- and μ^+.
  - vacuum, in flight, as μ^+e^-.
  - surrounding materials (μ^+e^- or μ^+).
- *Provides image of projection of decay locations in (y,z), as a function of time.*

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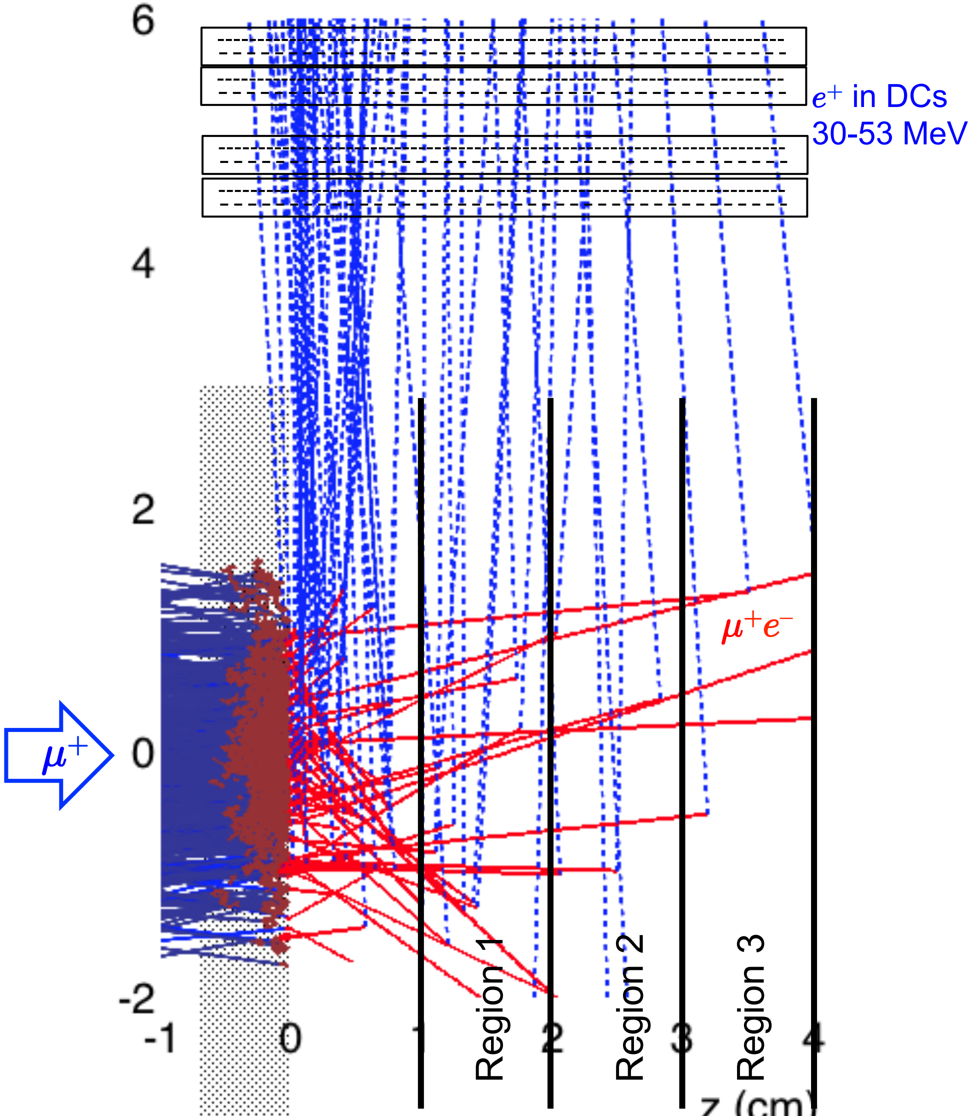

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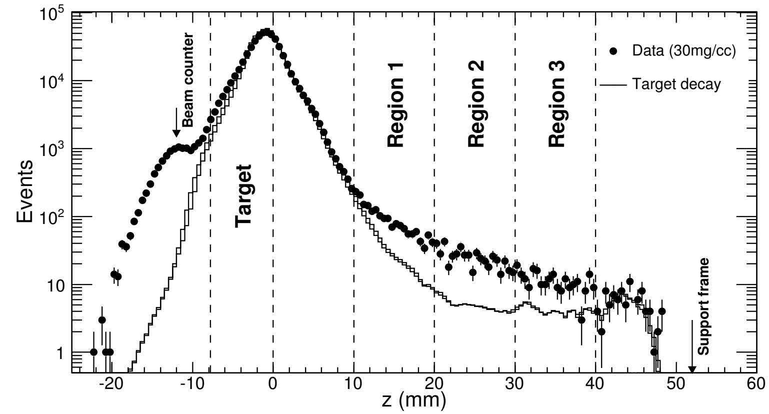
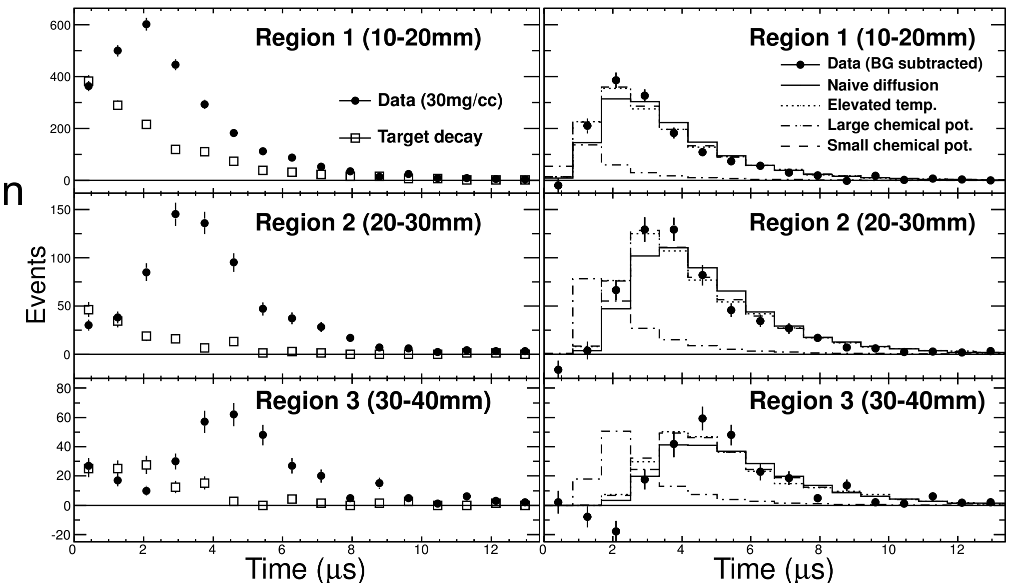
Mu in vacuum: 2010 and 2011

- Aerogel samples
  - all high uniform and optically transparent
  - different preparations
    - hydroscopic nature of surfaces
    - different densities: 27−180 mg/cm^3
- Procedure
  - low momentum subsurface μ^+
  - set to stop $\sim$50% in aerogel
- Observations
  - no obvious dependence of yield on density or preparation
- Partial yields $\sim$0.003
  - into regions 1−3, distance 10−40 mm from aerogel surface
  - normalized to all muon decays observed
    - *some care required to interpret yield expected with different beams and targets*

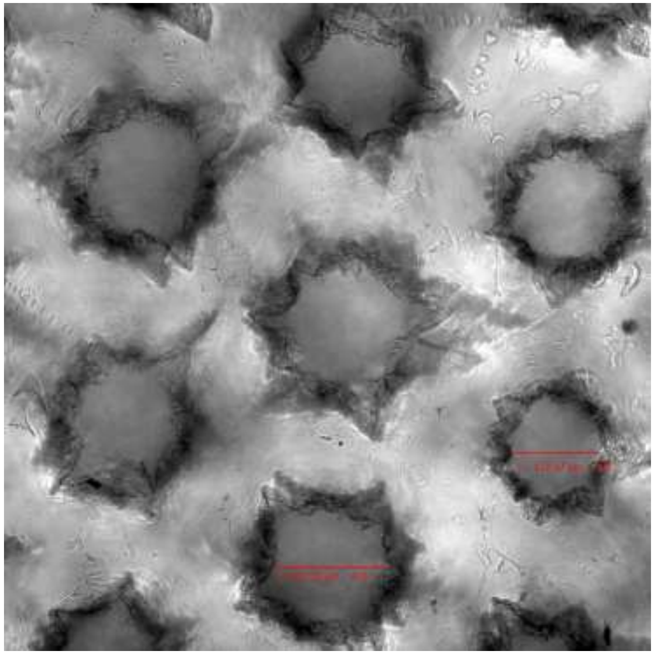


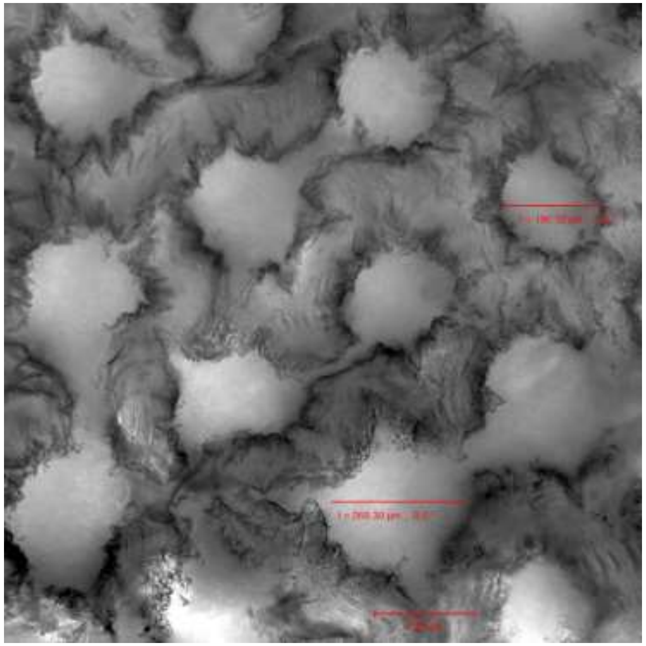


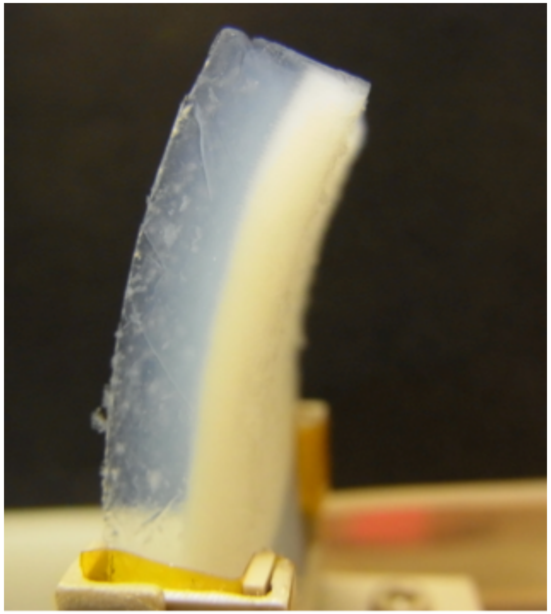
P. Bakule et al., Prog. Theor. Exp. Phys. 2013, 103C01 (2013).

Laser ablation of aerogel surface

- Simulations based on a diffusion model showed increased yields from structured surface (channels, holes) → laser ablation by RIKEN group







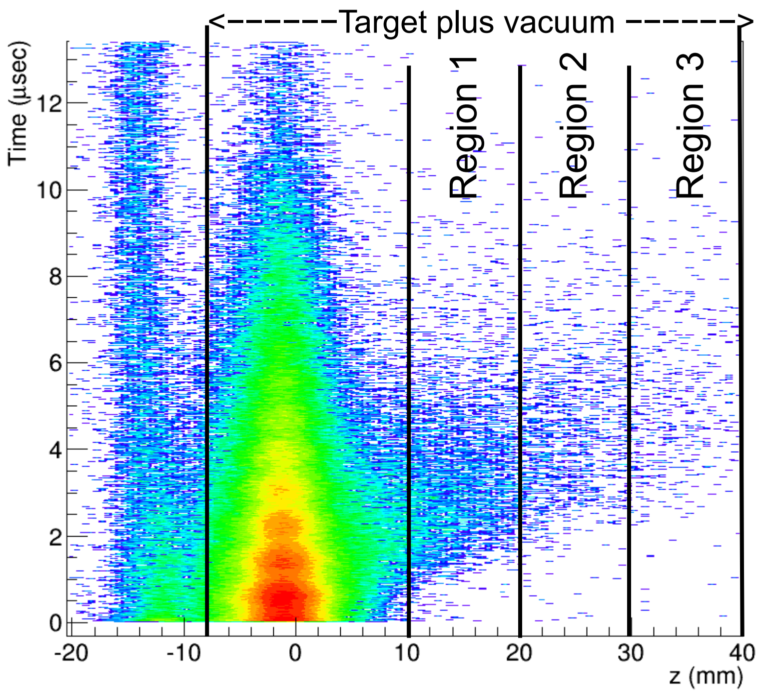
d = 170 μ, 220 μ
p = 500 μ

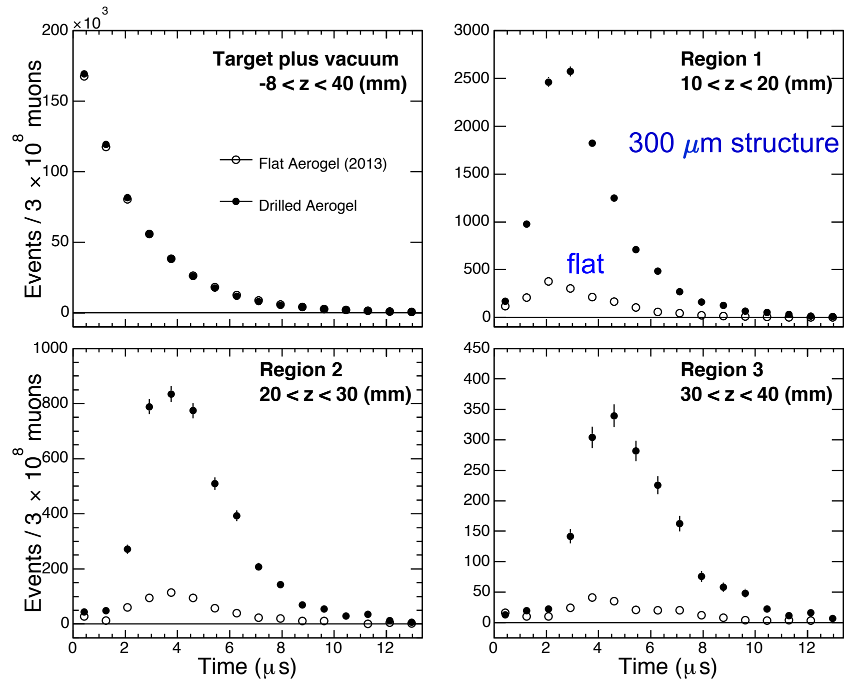
d = 200 μ, 270 μ
p = 375 μ

Images by S. Kamal, LASIR and Dept. of Chemistry, UBC.

Photo of laser-ablated aerogel used at TRIUMF. Curvature is due to the removal of material on the right.

Results of 2013 data





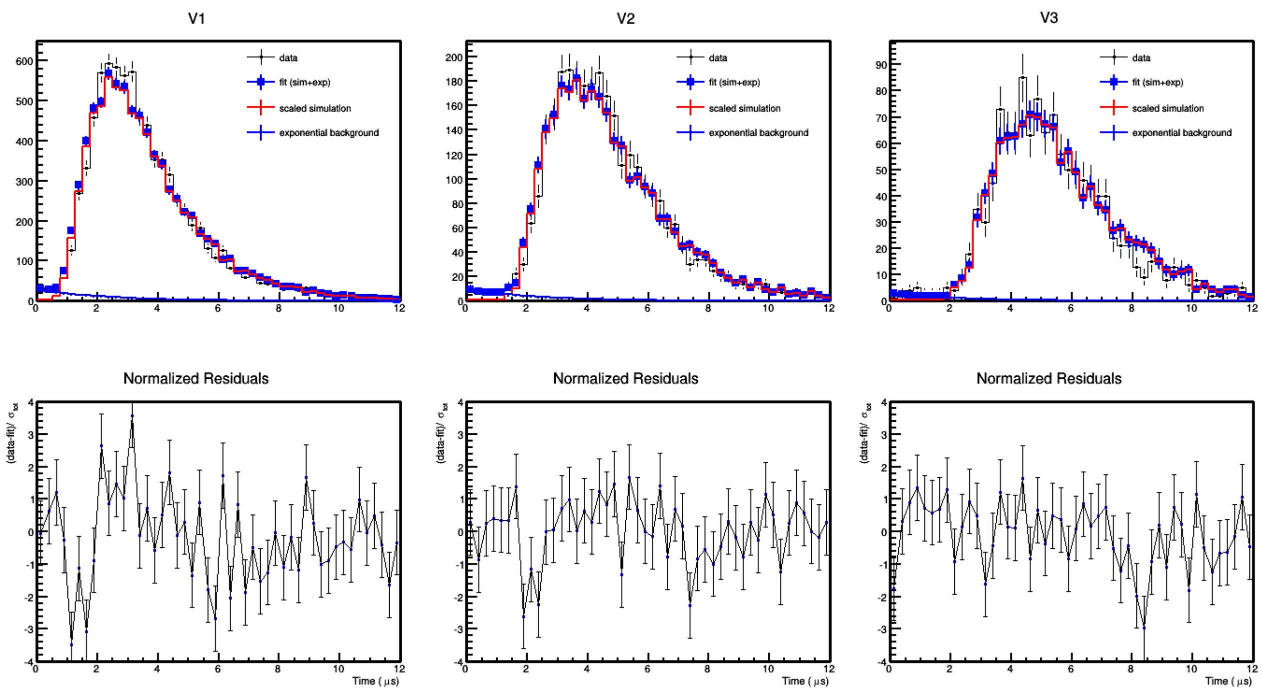
- Used a ***model-independent approach*** to estimate yields
- For 0.3 mm structure, observed ~10 times yield previously reported from 2011 data, 8 times yield found in similar flat target in 2013.
- Model-independent approach cannot independently estimate *total yield* or *partial yield near target* for laser ionization estimates
  - ➔ apply diffusion model analysis

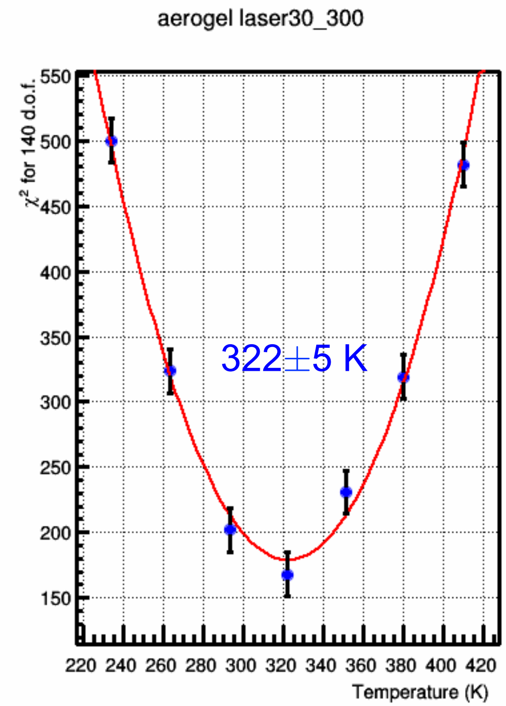
Table 1 Yield of Mu in the vacuum region 1–3. For all laser processed samples, the diameter of the structure is 270 μm.

Sample	Laser-ablated structure (pitch)	Vacuum yield (per 10^3 muon stops)
Flat	none	3.72 ± 0.11
Flat (Ref. [7])	none	2.74 ± 0.11
Laser ablated	500 μm	16.0 ± 0.2
Laser ablated	400 μm	20.9 ± 0.7
Laser ablated	300 μm	30.5 ± 0.3

G.A. Beer et al., Prog. Theor. Exp. Phys. 2014, 091C01 (2014).

Diffusion model analysis: ablated target





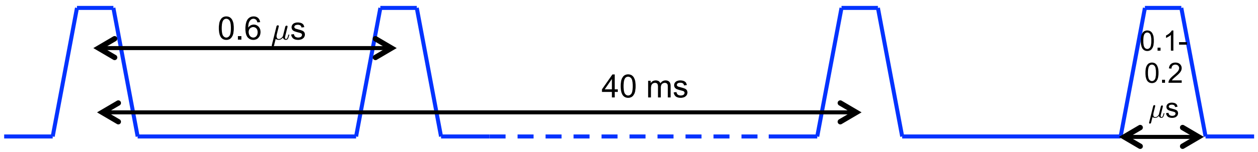
χ^2 of fits to simulations at different temperatures

- Laser ablated (pitch = 0.3 mm) aerogel:
  - much better signal to background enables more reliable diffusion model comparison
    - simultaneous fit to 3 vacuum regions at T=322 K shown
  - best fit emission velocities correspond to 322 ± 5(stat) K
  - D=870 ± 20 cm^2 s^{-1}, χ^2 = 168/140 (p=5%)
- Simulation results tell us
  - Mu yield and appearance time in region close to target surface
  - speed distribution is (near) thermal
  - yields under other conditions of muon stopping distribution, e.g., for J-PARC

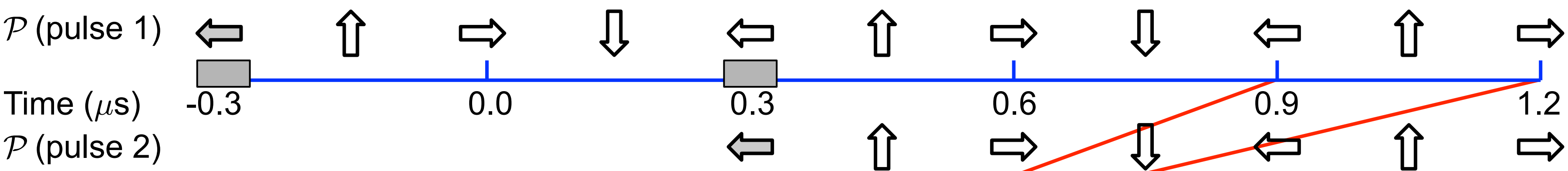
Diffusion simulation predicts rate, position, and time of Mu in vacuum to enable J-PARC g–2/EDM design

Spin manipulation of Mu ($\mu^+ e^-$) at rest

- J-PARC MLF beam: 25 Hz repetition, 2 pulses per repetition

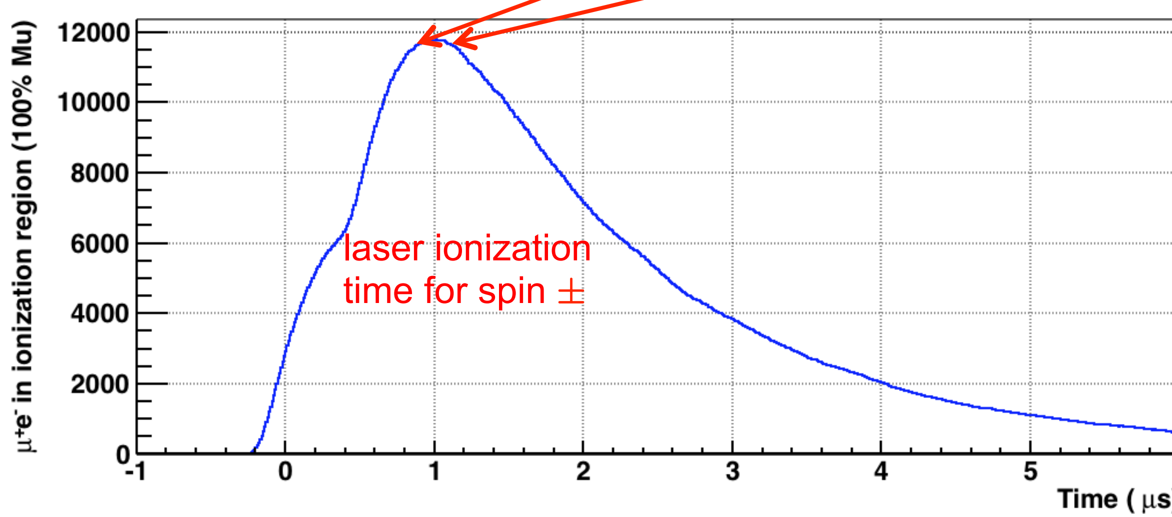


- 0.6 μs separation means that period of any Larmor precession of Mu must have a frequency that satisfies $(\omega/2\pi)\times$n = 1/(0.6 μs)
  - f = 0.14 MHz/mT ➔ 2π rotation in 0.6 μs occurs for B = n$\times$0.119 mT



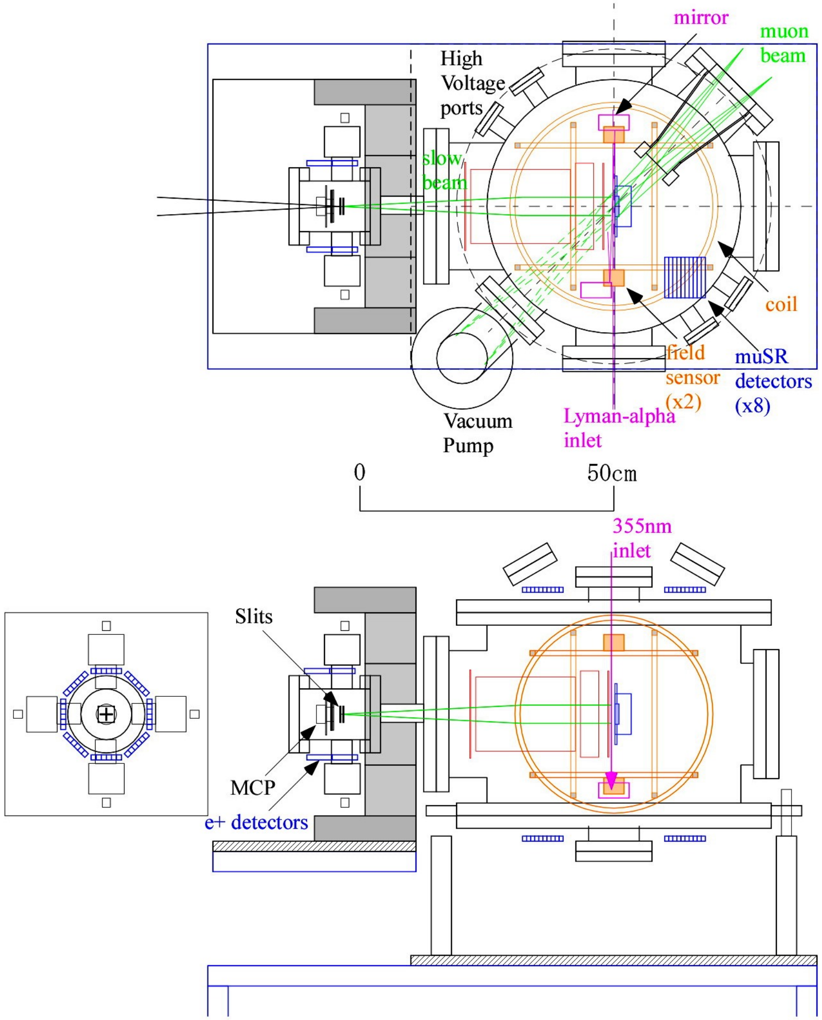
Simulation of Mu time distribution in vacuum for J-PARC beam.

“Siberian Snake” after low beta acceleration will provide independent spin flip.



Next steps for ultra-cold production

- Include laser and DC acceleration components with aerogel target
  - requires high intensity pulsed muon source
    - RIKEN beams at RAL
    - J-PARC MLF
- Continue aerogel emission R&D
  - verify model-dependent estimates at ≤ 5 mm from aerogel surface via laser ionization
  - confirm emission and aerogel survival adjacent to acceleration field
  - ablation parameter optimization
- Develop spin manipulation at rest
  - ω_L of Mu ➔ $\Delta\phi = \pi$ in 300 ns at 0.12 mT
  - arrays of decay detectors surrounding target
- Verify G4 simulation of Mu processes in non-uniform materials (ablated aerogel)



RIKEN/RAL ultra-slow muon apparatus (K. Ishida and S. Okada)

Summary

- A measurement of muon $g{-}2$ by J-PARC E34 with statistical uncertainty at the level of BNL E821 appears possible
  - E821 required time to understand and assess systematic uncertainties; E34 will also require experience to understand and minimize its different systematics.
- Muonium production via structured aerogel makes the Stage 1 goals for an ultra-cold muon beam feasible
  - further optimization may lead to higher $g{-}2$/EDM sensitivity

S1249 collaborators: G.A. Beer, J.H. Brewer, Y. Fujiwara, S. Hirota, K. Ishida, M. Iwasaki, S. Kamal, S. Kanda, H. Kawai, N. Kawamura, R. Kitamura, S. Lee, W. Lee, T. Mibe, Y. Miyake, S. Okada, K. Olchanski, A. Olin, Y. Oishi, H. Onishi, M. Otani, N. Saito, K. Shimomura, P. Strasser, M. Tabata, D. Tomono, K. Ueno, K. Yokoyama, E. Won

J-PARC $g{-}2$/EDM Collaboration:
$\sim$140 members from 49 institutions in 9 countries